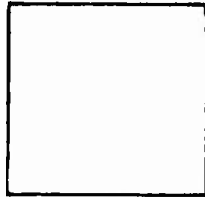


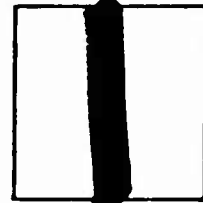
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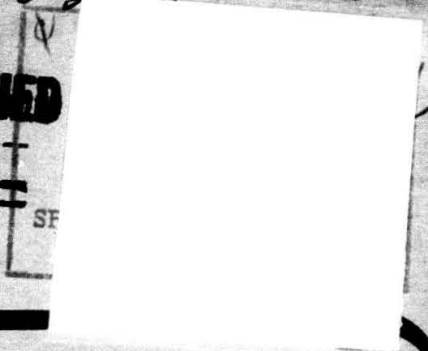
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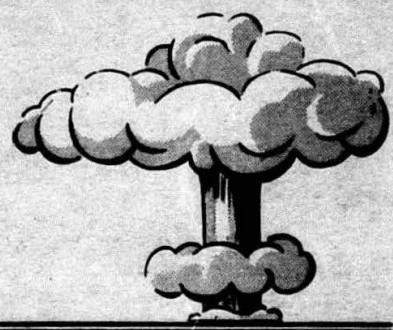
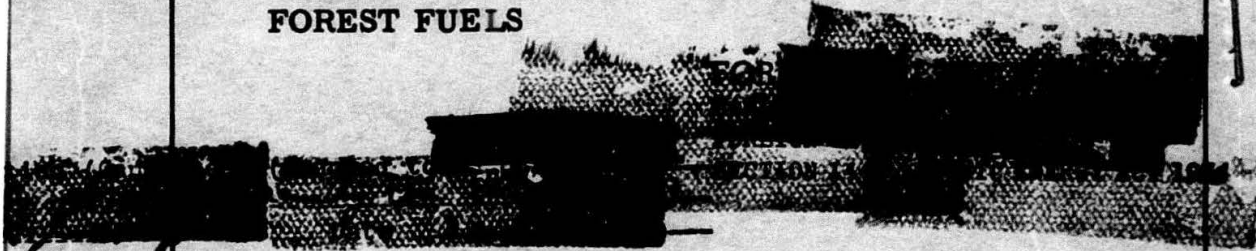
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THERMAL AND BLAST EFFECTS ON IDEALIZED
FOREST FUELS



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No. 205 of 352 copies, Series A

PROJECT 2.2

THERMAL AND BLAST EFFECTS ON IDEALIZED FOREST FUELS

by

A. A. Brown, Project Officer
R. K. Arnold
W. L. Fons
F. M. Sauer

29 April 1952

Division of Fire Research
Forest Service, U. S. Department of Agriculture

for

Operations Research Office, U. S. Army

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ABSTRACT

Project 2.2 was designed as part of an over-all study of atomic explosion effects on forests. This project studied frequency of persistent combustion in prepared and natural fuels at various distances from ground zero and appraised changes in persistent combustion associated with variations in density, thickness, and moisture content found in those fuels.

Prepared fuel beds of grass, punky wood, pine needles, and hardwood leaves were exposed at each of six stations -- 2,000, 4,000, 5,000, 7,000, 9,000, and 12,000 ft from ground zero. Three fuel beds at each station were covered until 15 minutes before shot time to keep fuel moisture content as low as possible. Thickness and density of fuel particles were determined prior to the test. Fuel moisture and fuel temperature at shot time were measured in duplicate fuel beds, similarly located but outside the test area. Naturally occurring fuels at the test site -- brush, grass clumps, and Joshua bark -- were studied before the tests and examined after each shot.

Post-test fuel examinations showed that punky logs and Joshua bark ignited and were consumed by fire at distances from ground zero where total thermal energy was approximately 3 cal/sq cm. These distances varied from 5,300 ft slant range for Shot Baker to 16,000 ft slant range for Shot Easy. Natural grass clumps ignited and were consumed by fire where total thermal energies approximated 4 cal/sq cm. Slant ranges varied from 10,650 ft for Shot Dog to 13,000 ft for Shot Easy. Other fuels exposed to a total thermal energy of 5 to 7 cal/sq cm ignited and were consumed by fire when the bed was exposed normal to the incidence of thermal radiation. Similar fuel beds exposed horizontally were only charred.

Conclusions based on results and observations from Operation BUSTER:

1. Under fire weather conditions^{1/} in a forest area, atomic explosions can be expected to ignite punky and fine grassy fuels whenever total thermal energy exceeds 3 cal/sq cm. For Operation BUSTER, Shot Easy maximum ignition distance was 16,000 ft slant range.

^{1/} Relative humidity less than 40 per cent, air temperature greater than 35° F, fuel moisture less than 15 per cent.

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2. For any given total energy level above 3 cal/sq cm a larger bomb is more likely to produce ignition than a smaller one, because larger bombs produce a given thermal energy farther from ground zero and combustion progresses farther before the blast wave arrives.

3. Fuel beds exposed perpendicular to the incidence of thermal radiation ignite farther from ground zero than fuel beds exposed horizontally. This phenomenon is due primarily to blast winds and moving sand which tend to wipe off any flame which has appeared on horizontal beds, but tend to drive similar flame into inclined beds. Difference in shape factor of the beds to the fire ball appears to be secondary to the sand blast effect.

4. Moisture content, density, and thickness appear to be critical factors which affect probabilities of forest fuel ignition following atomic explosions over forest areas.

5. Bomb-induced convection does not produce surface winds following blast-wind effects and need not be considered in the prediction of subsequent fire behavior.

Based on the above conclusions, as well as observations and data from which they were derived, these recommendations can be made:

1. Future effects tests with atom bombs:

- a. Detonation time should be set between 1200 and 1500 hours to allow hygroscopic fuels to reach a low moisture content.
- b. One of the conditions for postponement of shots should be relative humidity greater than 20 per cent for 2 hours prior to shot time. (This should be an important condition for most materials exposed to thermal effects.)
- c. Forest fuel beds for test purposes should be exposed perpendicular to the incidence of thermal radiation.
- d. Pure forest fuel types, similar to those exposed at Operation BUSTER, should be used again in conjunction with natural fuels.

2. Offensive use of atomic weapons in forest areas when thermal effects are important:

- a. Weather conditions in general should be dry and warm to insure that moisture content of fine, dead fuels is below 15 per cent.

- b. Drop days and times should be selected for maximum surface wind velocity and superadiabatic lapse rate.
- c. Drop time should coincide with or follow slightly after minimum relative humidity for the day.
- d. Possibilities of coordinating napalm or other incendiary bomb attacks with atomic bomb attacks should be investigated.

CHAPTER 1

OBJECTIVE

1.1 GENERAL

Project 2.2, Operation BUSTER, was an integral part of a study of consequences of atomic explosions on forests. This project was designed to fit into the over-all study in these ways:

1. To provide a field check for prior analytical work which sought to determine the frequency and pattern of persistent combustion in an idealized fuel subject to various radiation energies and to extrapolate these data to actual fuels as they occur in nature.

2. To provide a field check against which subsequent laboratory source tests may be scaled.

3. To provide preliminary evaluations of effects of moisture content, fineness or thickness, and density on the probability of ignition.

4. To study and experience problems associated with exposure of forest fuels to atomic explosions in order to design more intensive and effective field tests should laboratory and analytical studies indicate their necessity.

5. To study the effect of blast-wave winds on persistence of ignition.

More specifically, this project approached the above general objectives by providing tests which indicated:

1. Energies (distance from ground zero) at which sample fuel beds of common forest fuels were ignited by radiation following atomic explosions.

2. Effects of blast-induced winds on continued burning of ignited fuels.

3. Effects of fuel-moisture content on ignition and continued burning.

1.2 MILITARY SIGNIFICANCE

Simultaneous persistent ignition of forests over large areas centered around an atomic explosion normally will give rise to a fire

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storm which completely destroys anything remaining after bomb energies are dissipated. Moreover, conflagration-type fires which may spread from initially ignited areas are limited only by fuel and weather conditions. A forest area approximately 0.3 mile in diameter with fuel concentration of 100 tons per acre, as found in heavy brush cover, on burning would release energy equal to the total energy of a 20 KT atomic bomb. Consequently, data from this project are important to offensive and defensive military operations in wildland areas.

CHAPTER 2

HISTORICAL AND THEORETICAL

2.1 GENERAL

Previous work^{2/} on thermal effects of atomic explosions on forests analyzed ignition of thin forest fuels by thermal radiation. Two types of ignition were recognized in the analysis. "Spurious" or transient ignition disappears when the external source of heat is removed, and is of interest only for the small amount of heat it adds to that contributed by the thermal source. The other type was defined as complete or persistent ignition resulting in sustained combustion after the external source of heat is removed.

This previous analysis gave a preliminary estimate of the thermal energy required to ignite leaves and grass up to thickness of 0.025 cm.^{3/}

The following table shows for certain idealized forest fuels the calculated effect of moisture content and thickness on radius of ignition in feet from ground zero when exposed to thermal radiation from a 20 KT atomic explosion for visual range of 12 miles:

TABLE 2.1

Calculated Effect of Moisture Content and Thickness on
Radius of Ignition from a 20 KT Atom Bomb

Fuel*	Radius of Ignition in Feet from Ground Zero			
	Moisture Content, Per Cent of Dry Weight			
	0	10	20	30
Leaf (0.0167 cm thick)	7500	7100	6700	6400
Leaf (0.0083 cm thick)	8900	8500	8150	7850
Grass Blade (0.003 cm thick)	7800	7700	7550	7350

* Absorptivity used: Leaves, 0.8; grass blade, 0.5.

^{2/} Operations Research Office. Preliminary Study of the Consequences of an Atomic Explosion Over a Forest. ORO-T-108. Washington, 1950. 102 pp.
^{3/} Appendix A contains basic assumptions and formulae for this analysis.

CHAPTER 3

PREPARATIONS AND METHODS

3.1 PREPARED FUELS

Prepared fuels for Operation BUSTER were selected to obtain a wide range of thickness and specific gravity. A description of these fuels is found in Table 3.1 and Figures 3.1 through 3.6.

TABLE 3.1

Description of Prepared Fuel Beds

Fuel	Description	Thickness (Cm)	Density (Gm/cc)
Pine needles	<u>Pinus ponderosa</u> , on the ground 1-3 years	.038	0.51
Hardwood leaves	Madrone, <u>Arbutus menziesii</u> , freshly fallen	.028	0.45
Grass	Wheatstraw, <u>Triticum aestivum</u> , leaves and heads removed	.037	0.35
Punk	White fir, <u>Abies concolor</u> , small chunks of rotted heartwood	--	0.25
Sedge	<u>Carex geyeri</u> , cured, standing in clumps	.017	0.53
Punky logs	White fir, <u>Abies concolor</u> , logs 6" to 8" in diameter with finely shreaded rotted sapwood on outside	--	0.05

Pine needles, hardwood leaves, grass, and punk were arranged in trays 2'x4'x4", the tops of which were flush with the ground to approximate natural fuel conditions. Two-inch mesh chicken wire secured over each fuel bed prevented blast winds from blowing away the fuels. Preliminary tests indicated that this relatively small area of wire does

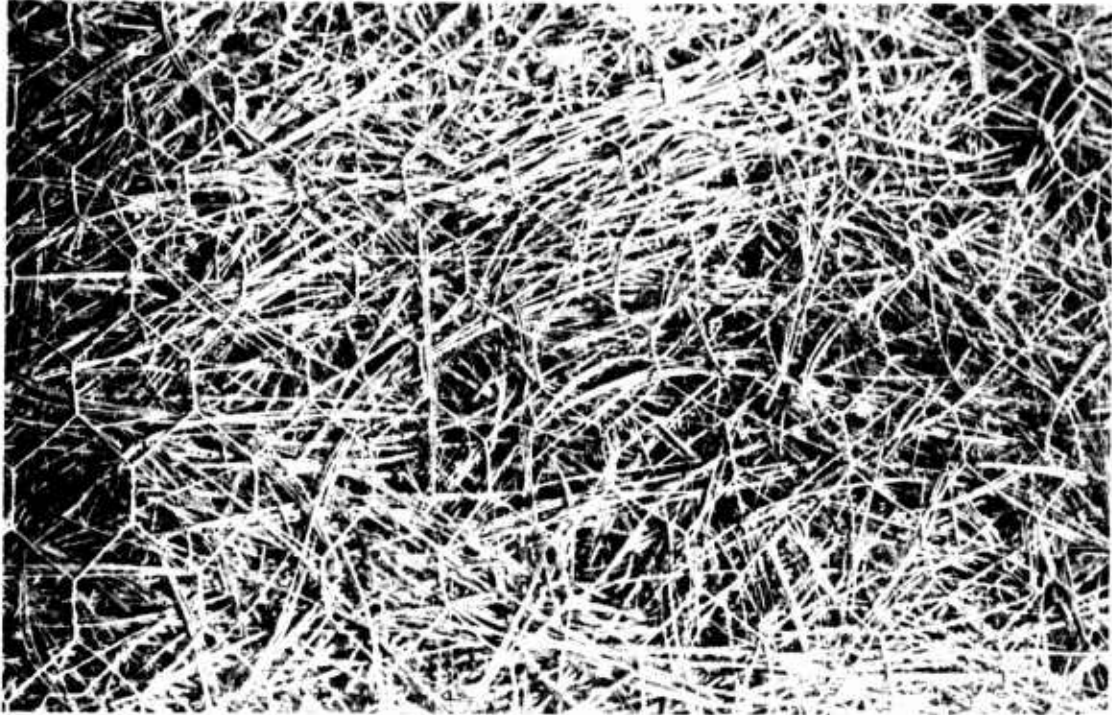


Figure 3.1 Pine Needle Fuel Bed

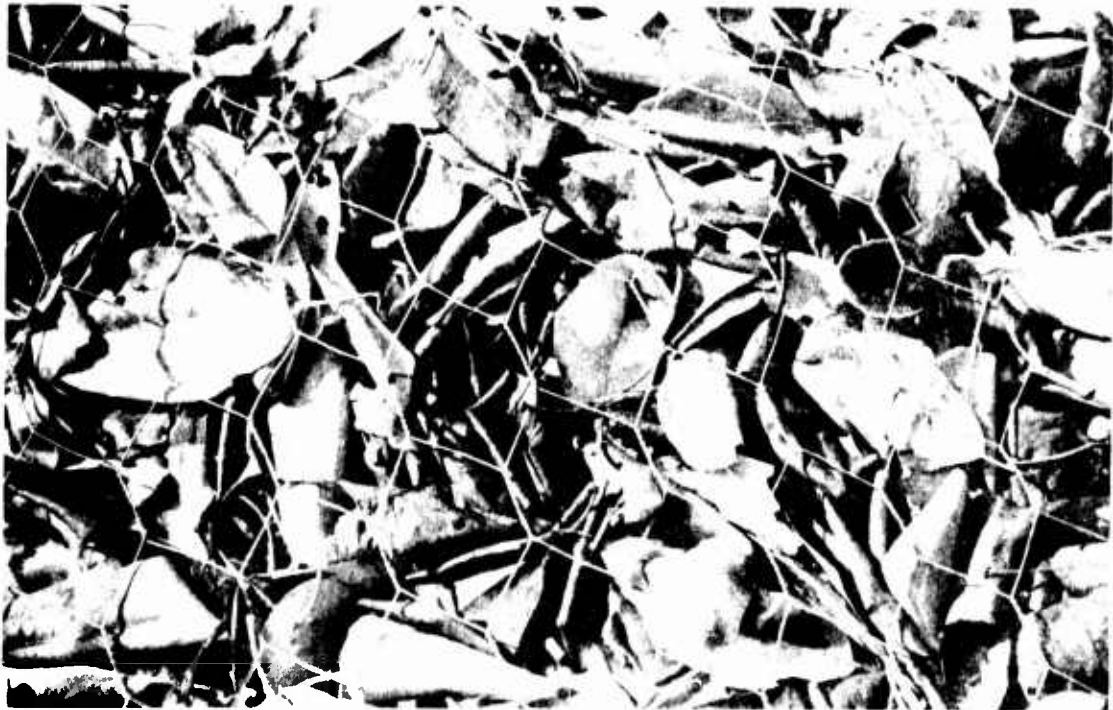


Figure 3.2 Madrone Leaf (Hardwood) Fuel Bed



Figure 3.3 Grass (Wheatstraw) Fuel Bed



Figure 3.4 White Fir Punk Fuel Bed



Figure 3.5 Sedge Fuel Bed



Figure 3.6 White Fir Punky Log

not affect ignition or continued burning. To eliminate the possibility of dew forming on all fuels, to protect them in case of rain, and to vary moisture contents (dew point permitting) some fuel beds at each station were covered with a waterproof window shade which was released by alarm clock 15 minutes before scheduled shot time.

Sedge was transplanted in clumps to 5-gallon cans, in turn exposed in groups of two forming a fuel bed 9 inches by 18 inches.

Punky logs, 6 to 8 inches in diameter, were cut 3 feet long. Sapwood on these logs was mostly rotten, fine shreaded wood.

Prepared fuels were exposed at six stations.

TABLE 3.2

Actual Horizontal Distances and Slant Ranges from Bomb Bursts to Stations

Station Distance from G Target (Feet)	Shots							
	BAKER		CHARLIE		DOG		EASY	
	Horizontal Distance (Feet)	Slant Range (Feet)	Horizontal Distance (Feet)	Slant Range (Feet)	Horizontal Distance (Feet)	Slant Range (Feet)	Horizontal Distance (Feet)	Slant Range (Feet)
2,000	2,140	2,410	2,165	2,440	2,057	2,500	4,680	4,820
4,000	4,140	4,290	4,165	4,320	4,057	4,300	6,550	6,690
5,000	5,140	5,260	5,165	5,285	5,057	5,250	7,550	7,670
7,000	7,140	7,230	7,165	7,280	7,057	7,200	9,500	9,590
9,000	9,140	9,210	9,165	9,230	9,057	9,180	11,450	11,520
12,000	12,140	12,180	12,165	12,220	12,057	12,145	14,400	14,450

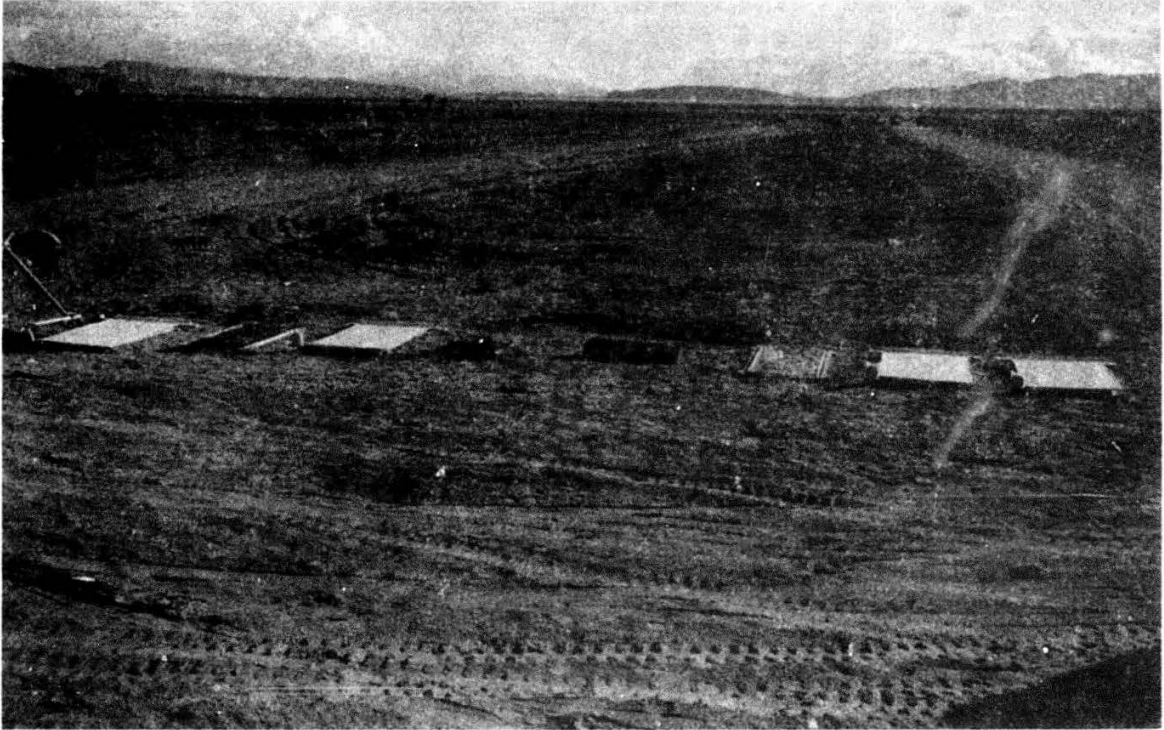


Figure 3.7 Arrangement of Fuel Beds at Stations

**NOTE: Four Fuel Beds Covered by Window Shades
To Be Released by Clock Mechanism**

3.2 NATURAL FUELS

TABLE 3.3

Natural Fuels Found at the Test Site

Fuel	Description	Thickness (Cm)	Density (Gm/cc)
Natural grass	Desert needlegrass, <u>Stipa speciosa</u> , dense mat of fine dead leaves at base.		
	- Leaves	.007	.534
	- Stalks	.098	
Brush	White bursage, <u>Franseria dumosa</u> , many dead twigs sparsely arranged.	.057 -.108	.562
	Jointfir, <u>Ephedra</u> spp., many dead twigs.	.072 -.119	.557
	Creosote bush, <u>Covillia tridentita</u> , few dead twigs, sparse green leaves.	--	--
Joshua bark	Joshua trees, <u>Yucca brevifolia</u> , 15 to 20 ft high with thick, cork- like bark covered by old dead leaves.	--	--

These fuels were distributed ideally for study of ignition from thermal effects of atomic explosions. Individual brush and grass clumps were far enough apart so that fire would not spread from one to the other.

Thick clumps of grass stalks, 6 to 12 inches high, provided some protection from blast winds for the fine, dead grass leaves clustered at their bases.

Thermal characteristics of bursage and jointfir were similar enough that they could be evaluated as one fuel type. They occurred in sparse clumps about 12 to 24 inches high. Approximately three clumps per acre had enough dead material under them to form a litter which would carry fire. Since creosote bush did not extend over the entire area studied, it was not used as an indicator of thermal effects.

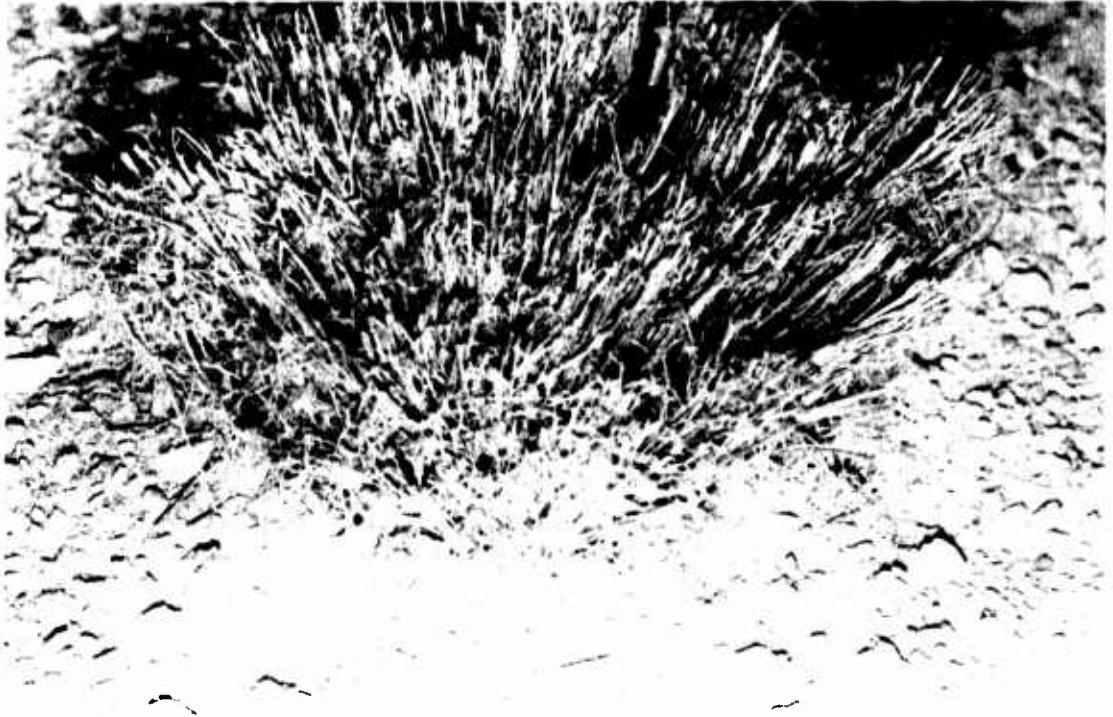


Figure 3.8 Natural Grass Clump Showing Dense Mat of Fine Leaves at Base

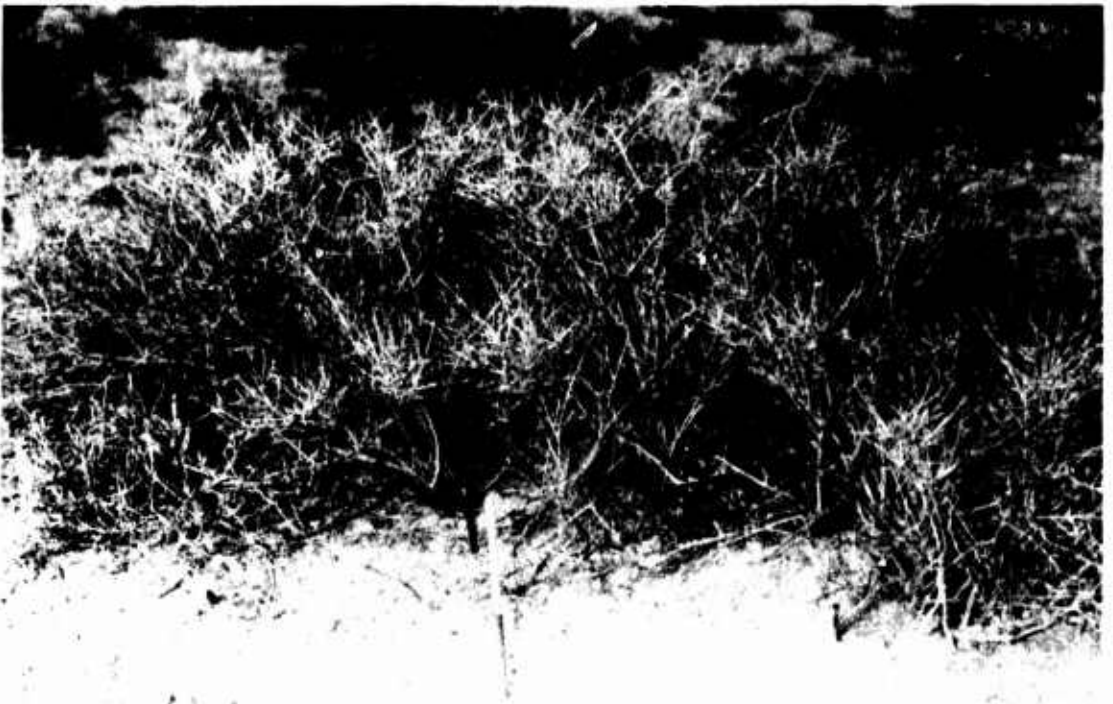


Figure 3.9 Natural Brush Clump



Figure 3.10 Joshua Tree Showing Bark Characteristics and Burn Following Shot Charlie. Figure 4.1 Shows This Bark Burning

Joshua trees were spaced 50 to 300 feet apart. Their coarse cork-like bark plates were covered by dead leaves which were fringed with fine, dead, hairy material which ignited rather easily. About 10 per cent of the Joshua trees were rotten along the main stem and these rotten spots provided punky materials similar to those of prepared punky logs.

3.3 OTHER DATA

A duplicate set of fuels was exposed to atmospheric conditions which approximated as closely as possible those of the test samples. At shot time fuel temperature was determined and fuel moisture samples were taken from these duplicate fuels and from natural fuels.

A pre-test photograph was made of each fuel bed and of each variation of natural fuel type. Post-test photos were taken to illustrate any significant thermal effects on these fuels.

Photography during the test was provided by the U. S. Naval Radiological Defense Laboratory, San Francisco. At the 7,000-foot and 9,000-foot stations two K-25 cameras operating at one frame per 0.6 sec. and eight GSAP cameras operating at 64 frames per sec. recorded ignition and combustion behavior during and after the shot.

CHAPTER 4

RESULTS

4.1 GENERAL

Official thermal studies were made on Shots Baker and Dog. However, natural vegetation and fuels unaffected by the previous shot were examined after Shots Charlie and Easy, thus giving data over a range of four detonations. Data for all shots, found in Tables 4.1, 4.2, and 4.3, are comparable when allowance is made for differences in fuel moisture content. Punky logs exposed at Shot Charlie provided the only exception, for they had previously been exposed to Shot Baker and had all the fine, rotten material sand-blasted from them. This lack of fine material on the log surface partly accounts for the fact that these logs did not burn at any distance after Shot Charlie.

TABLE 4.1

Thermal Effects of BUSTER Shots on Natural
Fuels -- Field Observations

Fuel	Slant Range in Feet				Minimum Thermal Energy ^a (Cal/sq cm)
	BAKER	CHARLIE	DOG	EASY	
Natural grass burned	0	0	6,450 to 10,600	6,140 to 12,930	-- 4
Natural grass charred	4,640	7,780	10,790	12,930	--
Brush burned	0	0	6,450 to 10,600 ^b	6,140 to 12,930 ^b	-- --
Brush charred	3,670	7,390	9,320	--	--
Joshua bark burned	4,150	7,090	9,910	16,040	2.6

^aFrom "BUSTER Thermal Preliminary Data for Use in Program 11 Reports."

^bBrush burned only when ignited by contiguous grass clumps.

TABLE 4.2

Thermal Effects of BUSTER Shots on
Prepared Fuels Exposed Horizontally

Slant Range (Feet)	Shot	Total Thermal Energy ^a (Cal/sq cm)	Thermal Effect ^b					
			Pine Needles	Hwd. Leaves	Grass	Punk	Sedge	Punky Log
I								
2,410	BAKER	18	SC	Burn	SC	Burn	Char	Char
2,440	CHARLIE	56	Burn	NVE	Char	--	--	Char
2,800	DOG	85	Burn	--	Burn	Char	--	--
4,830	EASY	51	Char	--	Char	--	--	--
II								
4,290	BAKER	5.1	NVE	SC	SC	Burn	Char	Burn
4,320	CHARLIE	18	SC	SC	SC	--	Char	--
4,300	DOG	28	SC	Char	Char	Burn	Char	Char
6,680	EASY	15	Char	Char	Char	--	--	--
III								
5,260	BAKER	5.2	NVE	NVE	NVE	NVE	SC	Burn
5,255	CHARLIE	12	NVE	SC	SC	Char	Char	--
5,250	DOG	18	SC	Char	Char	Burn	Char	Burn
7,670	EASY	12	Char	Char	Char	Burn	--	--
IV								
7,230	BAKER	1.6	NVE	NVE	NVE	NVE	NVE	NVE
7,250	CHARLIE	6.4	--	NVE	NVE	NVE	Char	Char
7,200	DOG	9.4	SC	SC	Char	Burn	Char	Burn
8,590	EASY	7.3	Char	Char	Char	Burn	--	--
VI								
9,210	BAKER	--	--	--	--	NVE	NVE	NVE
9,230	CHARLIE	4.0	--	--	--	--	NVE	NVE
9,180	DOG	5.6	--	NVE	SC	SC	Char	Burn
11,520	EASY	5.0	--	SC	SC	SC	Burn	Burn
VII								
12,180	BAKER	--	--	--	--	--	NVE	NVE
12,220	CHARLIE	2.3	--	--	--	--	--	--
12,145	DOG	5.2	NVE	NVE	NVE	NVE	NVE	Burn
14,450	EASY	5.2	--	NVE	--	--	NVE	Burn

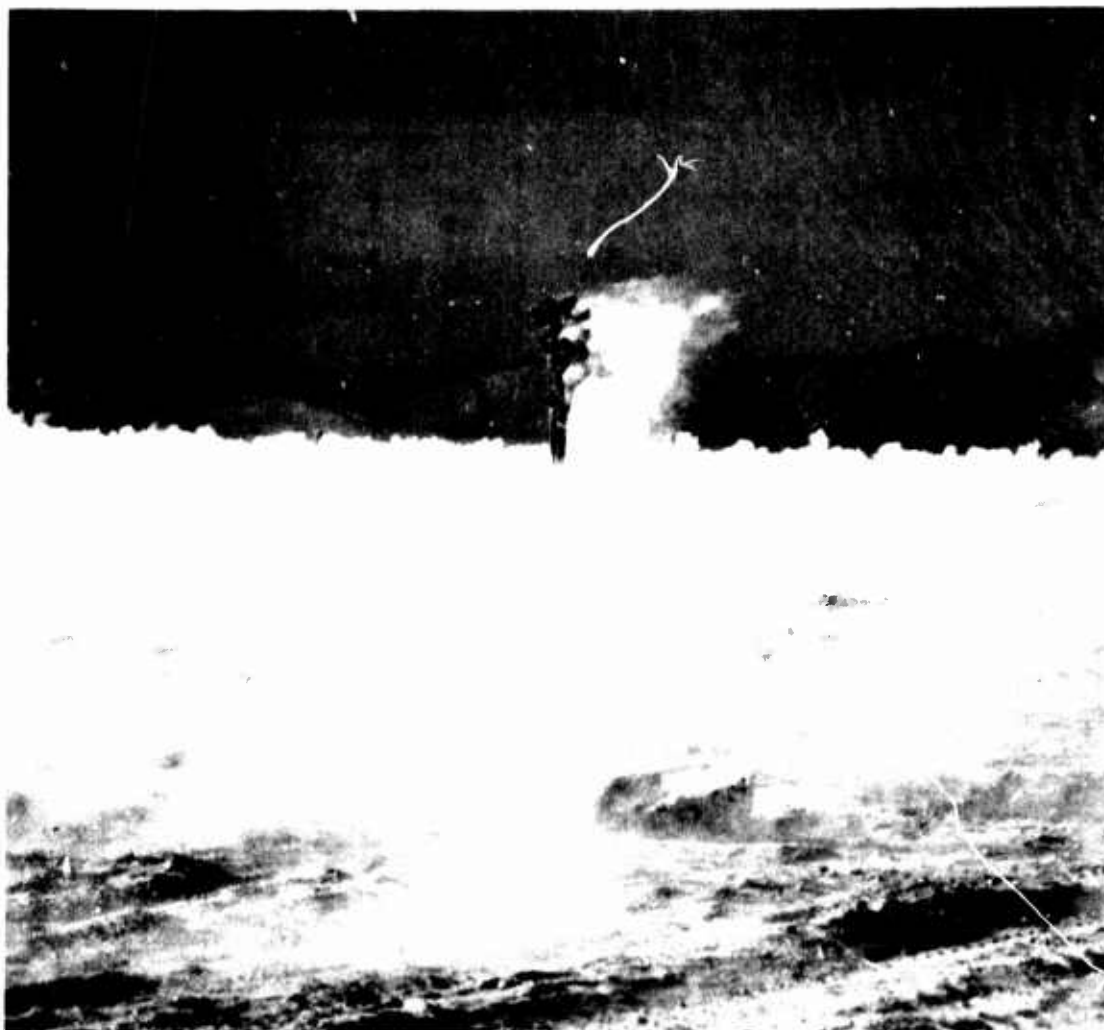
^aFrom "BUSTER Thermal Preliminary Data for Use in Program 11 Reports."

^bBurn - Fuel completely consumed by fire

Char - Fuel partially burned before being extinguished by blast-wave winds

SC - Fuel slightly charred

NVE - No visible effect



**Figure 4.1 Joshua Tree and Sedge 7,000 ft from Ground
Zero Burning After Shot Charlie**

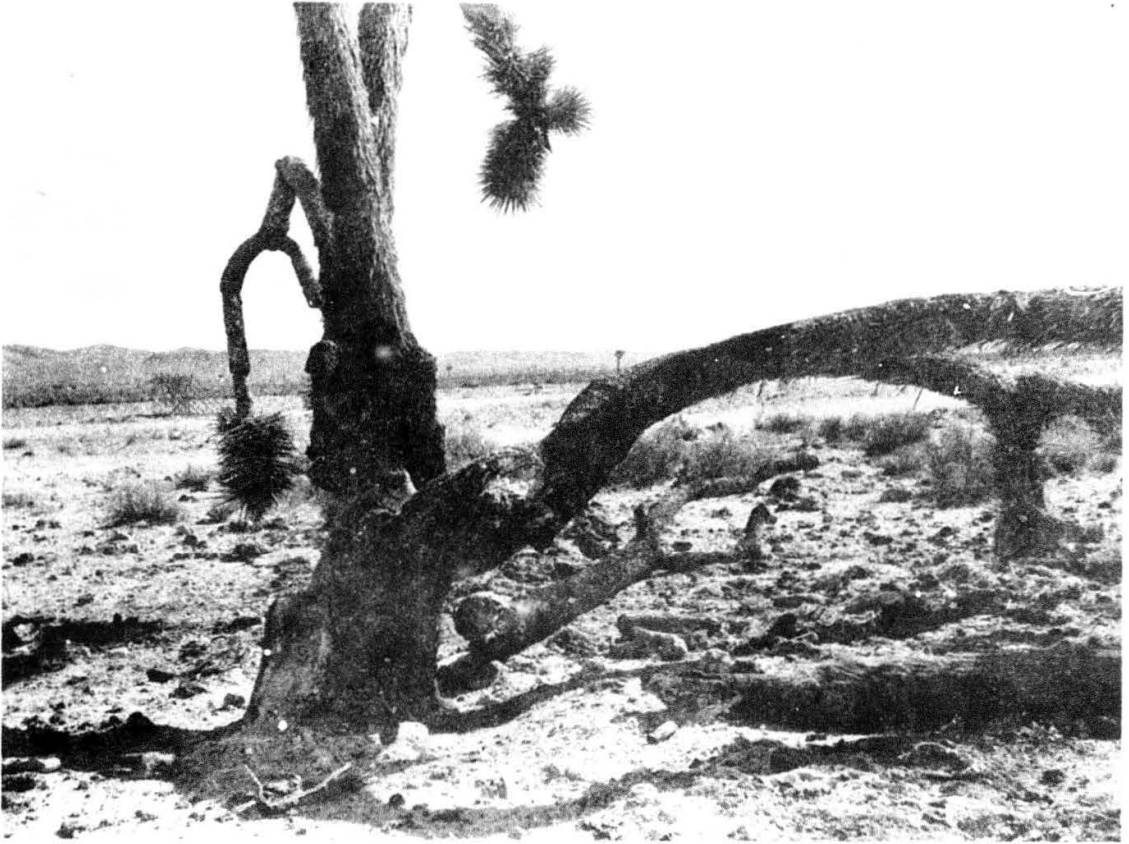


Figure 4.2 Joshua Tree Burn 6,000 ft from Ground
Zero Following Shot Charlie

TABLE 4.3

Thermal Effects of Shot Easy on Prepared Fuels
Exposed Normal to Incidence of Thermal Radiation

Slant Range (Feet)	Total Thermal Energy* (Cal/sq cm)	Thermal Effect		
		Pine Needles	Hardwood Leaves	Grass
6,680	15	Burn	Burn	Burn
7,670	12	Burn	Burn	Burn
9,590	7.8	--	Burn	Burn
11,520	5.0	--	Burn	Burn

*From "HUSTER Thermal Preliminary Data for Use in Program 11 Reports."

4.2 FUEL MOISTURE

Dead forest fuels are hygroscopic and react to changes in relative humidity with changes in fuel moisture towards equilibrium moisture content. Fuel moistures for each shot, Table 4.5, approximate equilibrium moisture content for relative humidity conditions as given in Table 4.4.

Difficulties associated with moisture-content determination for sample fuels exposed to atomic detonation are illustrated by the probability that data for Shot Baker are too low. Due to soil differences, surface soil moisture from rain 30 hours before was lower at the fuel sample site than along the thermal line at the test site. Relative humidity just above the ground, therefore, was lower at the fuel-sample site and measured moisture contents there were lower than those of materials on the thermal line.

TABLE 4.4

Weather Conditions Prior to Shot Time*

Time (Hours)	BAKER		CHARLIE		DOG		EASY	
	Temp. (°F)	Rel.Hum. (%)	Temp. (°F)	Rel.Hum. (%)	Temp. (°F)	Rel.Hum. (%)	Temp. (°F)	Rel.Hum. (%)
H - 6	44	60	37	80	45	53	58	42
H - 5	44	59	36	82	44	55	54	42
H - 4	44	58	35	90	43	59	54	42
H - 3	43	61	35	95	42	57	46	41
H - 2	42	62	32	100	43	59	50	36
H - 1	42	65	31	100	46	59	54	30
H - ½			35	100				
H	56	65	40	80	53	50	55	27

*Weather conditions apply along the thermal line 2 ft above the ground. Data were obtained from hygrothermograph readings closely checked by sling psychrometer at H - 9 hours and H + 6 hours. Relative humidity data are subject to errors of ± 5 per cent.

Fuel moisture effects were checked in the field after each shot. Fifteen minutes after Shots Baker and Charlie light fuels such as sedge, grass, and pine needles would not continue to burn when ignited by match flame. After Shot Dog comparable tests produced slow but persistent combustion. After Shot Easy these fuels burned rapidly following ignition by match flame. Moisture content differences partially explain why grass clumps were not ignited during Shots Baker and Charlie but were readily ignited 10,500 ft and 12,850 ft from ground zero during Shots Dog and Easy, respectively.

TABLE 4.5

Fuel Moisture Content at Shot Time^a

Fuel	Moisture Content in Per Cent			
	BAKER ^b	CHARLIE	DOG	EASY
Pine needles (covered)	10		10	
Pine needles (uncovered)	10		10	7
Hardwood leaves (covered)	10		9	
Hardwood leaves (uncovered)	11		11	7
Grass (covered)	9		9	
Grass (uncovered)	10		9	
Punk (covered)	11		7	6
Punk (uncovered)	11		10	
Sedge	10		11	
Punky log	12		10	8
Natural grass	10	13	9	4
Bursage	13	14	9	
Joshua bark	8		6	

^aFuel moisture data are subject to errors of ± 2 per cent.

^bRecorded moisture contents probably 2 to 4 per cent low.

Fuel temperatures approximated air temperature at shot time.

Thermal effects tests should avoid early morning shot times if possible. Not only are fuel moistures near their diurnal maximum, but determination of fuel moisture is most difficult when relative humidity is changing as much as 10 to 20 per cent in 30 minutes and solar irradiation is just beginning to heat surface layers of fuel. If, as during Shot Charlie, there is a strong inversion layer near the ground, relative humidity applicable to exposed fuels must be measured adjacent to those fuels. Lower relative humidity and thus lower fuel moisture in Joshua bark 10 feet above the ground and above the inversion layer partly account for the burning of Joshua bark at Shot Charlie when punky logs in higher relative humidity under the inversion layer did not burn. Maximum thermal effects might have been produced during these tests had shot time been set between 1200 and 1500 hours when relative humidity often was 10 per cent or lower.

Window shades used to cover fuels until 15 minutes before shot time did not lower fuel moisture significantly in terms of ignition and fire behavior. In fact, the one recorded effect of covers was on Shot Baker where covered pine needles and covered grass at Station I were charred slightly more than comparable uncovered fuels. Had window shades been used on Shot Charlie, however, fuel moisture undoubtedly would have been considerably lower for covered fuels since the dew point was reached for several hours prior to shot time.

4.3 COMPARISON OF LABORATORY AND FIELD DATA

Fuels exposed at Operation BUSTER have been exposed to the Laboratory Source at the University of California, Los Angeles, under contract by the Forest Service.

Data in Table 4.6 indicate that more energy is required to ignite forest fuels by the Laboratory Source than by atomic bomb sources.

Since the Laboratory Source operates at 5,000° F, the average absorptivity of fuels in relation to thermal energy from it is lower than comparable average absorptivity from bombs. This factor combined with differences in pulse shape may account for differences illustrated in Table 4.6.

Actually the only true minimum energy requirements obtained in the field were for natural grass and Joshua bark. Other fuels were exposed at 1,000- to 2,000-ft intervals, and energies are not necessarily minimum values. Ponderosa pine in a vertical position was not exposed to less than 12 calories.

TABLE 4.6

Minimum Energy Requirements for Persistent Ignition
 -- Fuels Exposed During Operation BUSTER

Fuel	Fuel Moisture Content (Per Cent)	Minimum Energy for Ignition (Cal/sq cm)	
		BUSTER Shots	Laboratory Source
Pine needles	7	12*	10.4
Hardwood leaves	7	5*	8
Grass	6	5*	7.2
Punk	11	5*	--
Sedge	5	5*	9.2
Punky log	12	3.2*	4.0
Natural grass	4	4	4.6
Joshua bark	--	2.6	--

*True minimum energies may be less than these values because these fuels were not exposed to smaller total energies.

4.4 EFFECT OF BLAST WINDS ON IGNITION

Prior to these tests it had been assumed that roughness of forest fuel bed surfaces would compensate for differences in absorbed thermal energy which would arise between fuel beds perpendicular to incidence of thermal energy and fuel beds placed horizontally. However, other than punk and punky logs there was no consistent persistent ignition effect on prepared fuels exposed horizontally to Shots Baker, Charlie, and Dog. As a check some duplicate fuel beds were exposed perpendicular to the incidence of thermal radiation on Shot Easy. In every case, as shown in Table 4.3, fuel beds exposed perpendicularly ignited and completely burned while comparable beds exposed horizontally were either charred or partially burned. It is probable that the original roughness assumption was invalid when applied to fuel beds instead of individual fuel particles. Also probably more important is the effect of blast-

wave winds and accompanying sand blast which tend to wipe initial flame off horizontally exposed beds while driving it into perpendicularly exposed beds.

On Shot Dog grass clumps were ignited between slant ranges of 6,450 ft and 10,600 ft from ground zero. Failure of grass to burn completely below the inner limit is associated with length of burning time before blast winds arrive and with blast-wind velocity. Natural grass clumps burned up in about 6 seconds after ignition by match flame. Thus, grass clumps beyond 7,000 ft were completely consumed by fire before the blast wave arrived.

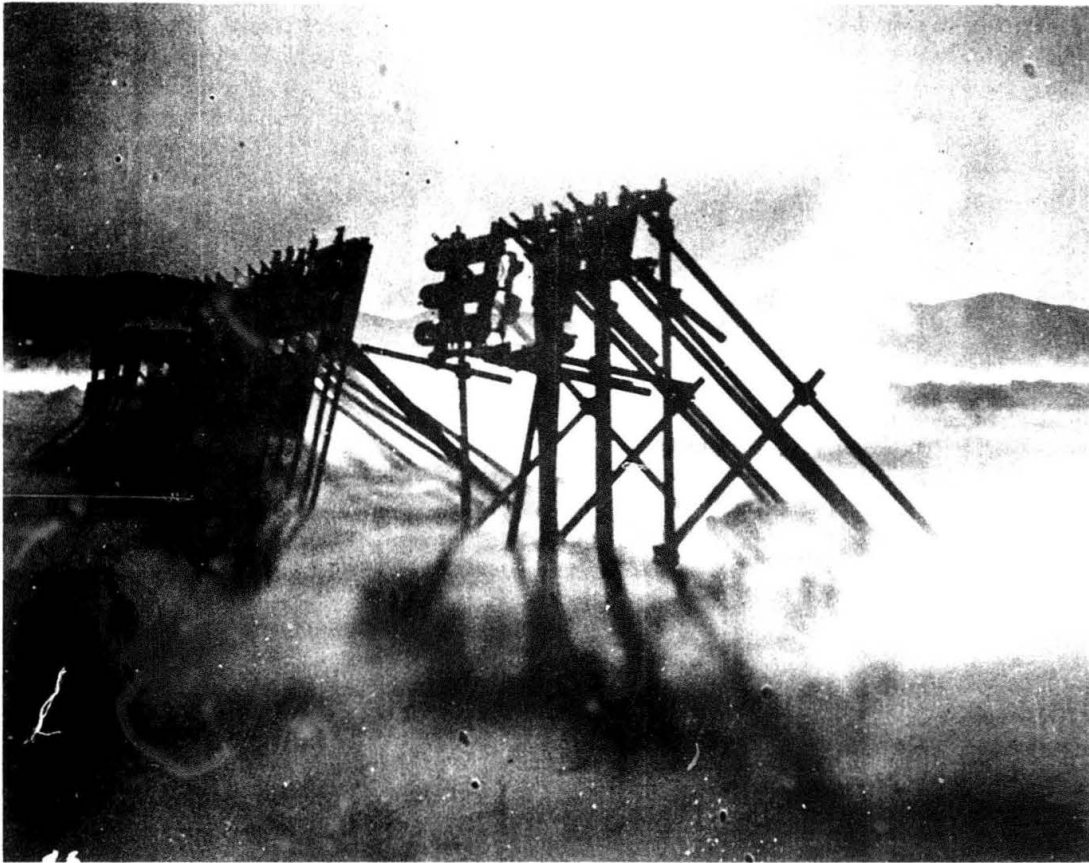


Figure 4.3 Blast-Wave Winds and Accompanying Sand Blast
5,000 ft from Ground Zero Following Shot Baker

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

1. Under fire weather conditions^{4/} in a forest area atomic explosions can be expected to ignite punky and fine grassy fuels whenever total thermal energy exceeds 3 cal/sq cm. For Operation MUSTER, Shot Easy maximum ignition distance was 16,000 ft slant range. Under similar conditions persistent ignitions in heavy grass and hardwood leaves can be expected whenever total thermal energy exceeds 3 calories. The latter energy level is not important, for nearly all forest areas have considerable punky or fine grassy material which when ignited spread flame to other fuels.

2. For any given total energy level above 3 cal/sq cm a larger bomb is more likely to produce ignition than a smaller one, because the larger bomb produces required thermal energy farther from ground zero and combustion progresses farther before the blast wave arrives.

3. Fuel beds exposed perpendicular to the incidence of thermal radiation ignite at lower total thermal energy than fuel beds exposed horizontally.

4. Moisture content, density, and thickness appear to be critical factors which affect probabilities of forest fuel ignition following atomic explosions over forest areas. Moisture content is probably the most important variable affecting ignition of common forest fuels. Density is important as an indicator of thermal conductivity,^{5/} while thickness of the fuel particle determines the maximum temperature to which the fuel surface can rise during the thermal pulse. Fuels of thickness less than 0.001 inch (natural grass leaves) respond as though their thermal conductivity were infinite.

^{4/} Relative humidity less than 40 per cent, air temperature greater than 55° F, fuel moisture less than 15 per cent.

^{5/} U. S. Dept. of Agriculture, Forest Service, Division of Fire Research. Thermal Conductivity of Some Common Forest Fuels. Phase Report for Operations Research Office, The Johns Hopkins University. October 1951. 10 pp.

5. Bomb-induced convection does not produce surface winds following blast-wind effects and need not be considered in the prediction of subsequent fire behavior. This phenomenon was studied by observing smoke and sand movement and was confirmed by motion pictures.

6. Attenuation of blast winds by forest cover will have an important effect on persistence of ignition. If there is considerable attenuation there will be less blowing-out of initial ignition points. On the other hand, attenuation will reduce breakage of limbs, and there will be less fuel on the forest floor to burn.

5.2 RECOMMENDATIONS

Based on the preceding conclusions, as well as observations and data from which they were derived, these recommendations can be made:

1. Future effects tests with atom bombs:

- a. Detonation time should be set between 1200 and 1500 hours to allow hygroscopic fuels to reach a low moisture content.
- b. One of the conditions for postponement of shots should be relative humidity greater than 20 per cent for 2 hours prior to shot time. (This should be an important condition for most materials exposed to thermal effects.)
- c. Forest fuel beds for test purposes should be exposed perpendicular to the incidence of thermal radiation.
- d. Pure forest-fuel types, similar to those exposed at Operation BUSTER, should be used again in conjunction with natural fuels.
- e. Complete surface weather data and continuous records of fuel moisture should be made at the actual test site.
- f. A more critical study of blast effects on persistence of ignition should be made.

2. Offensive use of atomic weapons in forest areas when thermal effects are important:

- a. Weather conditions in general should be dry and warm to insure that moisture content of fine, dead fuels is below 15 per cent.

- b. Drop days and times should be selected for maximum surface-wind velocity and superadiabatic lapse rate.
- c. Drop time should coincide with or follow slightly after minimum relative humidity for the day.
- d. Possibilities of coordinating napalm or other incendiary bomb attacks with atomic bomb attacks should be investigated.

APPENDIX A

IGNITION OF FOREST FUELS BY THERMAL RADIATION

A.1 GENERAL

The following analysis was extracted from a preliminary analytical study^{1/} which was made to estimate energies required to ignite thin forest fuels such as leaves and grasses. For heavier fuels, including punky logs, a uni-directional heat flow equation was given with appropriate boundary conditions. By numerical computations an estimate of energies required to ignite heavier fuels by thermal radiation is made possible.

A.2 ASSUMPTIONS

The analysis for thin fuels was based on these assumptions:

1. Fuels will be in the form of thin flat plates.
2. The moisture component in the fuel will have all the properties of free water.
3. Volatile substances will constitute 70 per cent of the dry weight of the fuel and will be treated as a single substance having a boiling temperature of 625° K and a latent heat of vaporization of 100 calories per gram.
4. Thermal conductivity of the laminar fuel is infinite, hence no temperature gradient exists within the fuel and heat is lost from both sides at equal rates.
5. Specific heat of the fuel will be different in different stages of the heating process, but remains constant when the mass of the fuel is not changing.
6. Heating by radiant energy is sufficiently rapid that no appreciable amount of water or volatile products is lost by diffusion, but only by boiling action.

^{1/} Operations Research Office. Preliminary Study of the Consequences of an Atomic Explosion Over a Forest. ORO-T-108, Appendix I, pp 80-93. Washington, 1950.

7. Ignition occurs when residual carbon reaches 900° K.

Assumption 1 is reasonable for that component of a heterogeneous fuel which is most likely to ignite. Assumption 2 is a close approximation if the moisture content M is increased by .02 (i.e., by 2 per cent). This procedure compensates for extra heat required to separate bound water from wood. For this reason, the true moisture content will be 2 per cent less than the values of M (except zero) used in this analysis. Assumption 3 is not quite as good as assumption 2, but better information on latent heat of vaporization of volatile products should make it as good as assumption 2. There is considerable variation in the boiling temperatures of volatile products of wood, and their latent heats of vaporization range from about 70 cal/g for turpentine to more than 200 cal/g for some of the alcohols. However, for most of the products these values average about 100 calories per gram. Assumption 4 is not very good even for thin fuels because of their low thermal conductivity. Nevertheless, there are compensating factors which make it considerably better than the temperature gradients within even thin fuels would indicate. For example, the mean temperature of an irradiated leaf is much less sensitive to variation in thermal conductivity than is the temperature difference between the two surfaces. Also, transient ignition which may occur on the hotter side of the leaf furnishes a small amount of heat which compensates for the higher rate of heat loss in an irradiated leaf of low thermal conductivity. Assumption 4 is best for partially transparent fuels, like thin grass blades, because the penetration of radiation gives more uniform heating. Assumption 5 is undoubtedly good if the mean specific heat over a given temperature range is known. Because of the short effective life (about 3 seconds) of the fireball, assumption 6 should be a good approximation.

A.5 ANALYSIS

The amount of heat required to bring a fuel sample of mass $\delta V(1+M)$ up to the ignition temperature is

$$Q = \delta V \{ C_f (T_v - T_0) + M [L_w + C_w (T_w - T_0)] + f L_v + (1-f) C_c (T_1 - T_v) \} \quad (A.1)$$

where,

C_f = specific heat of oven dry fuel (0.50 cal/g deg C)

$C_w = 1$ = specific heat of water

C_c = specific heat of carbon (0.20 cal/g deg C)

$f = 0.70$ = fraction of dry weight of fuel which will volatilize

L_w = latent heat of vaporization of water (540 cal/g)

- L_v = latent heat of vaporisation of volatile products (100 cal/g)
 M = moisture content of fuel expressed as a fraction of the oven dry weight
 Q = quantity of heat in calories
 T_1 = 900° K = ignition temperature
 T_0 = 300° K = initial temperature of fuel and surroundings
 T_w = 375° K = boiling temperature of water
 T_v = 625° K = boiling temperature of volatile products
 V = volume
 δ = 0.60 = density of oven dry fuel

This equation gives the net amount of heat necessary to raise the temperature of a fuel sample from T_0 to the ignition temperature T_1 . Depending on the intensity of radiation, the actual amount of heat will be somewhat greater owing to losses from radiation and convection.

For that time in which the fuel is not boiling off volatiles, the thermal energy balance for a leaf of Area A , absorbing energy at rate I , is

$$\frac{dQ}{dt} = [I - 2 \phi(T)] A$$

where $\phi(T)$ is a function representing rate of heat loss per unit area of one side of the thin fuel of thickness ℓ . If one assumes infinite thermal conductivity, the rate of heat gain, $\frac{dQ}{dt}$, may be written as

$$\frac{dQ}{dt} = \ell v c \frac{dT}{dt} = \delta \ell A C \frac{dT}{dt}$$

hence

$$\delta \ell C \frac{dT}{dt} = I - 2 \phi(T) \quad (\text{A.2})$$

The specific heat C takes on different values in the intervals $T_w - T_0$, $T_v - T_w$, and $T_1 - T_v$.

The function $\phi(T)$ is

$$\phi(T) = h(T - T_0)^{5/4} + \sigma \epsilon (T^4 - T_0^4)$$

where $h(T - T_0)^{5/4}$ is the rate of heat loss assuming free convection only,^{2/} and $\sigma \epsilon (T^4 - T_0^4)$ is the rate of heat loss by radiation. Since the absorbed irradiance I is a function of time, equation A.2 cannot be integrated directly. However, the function $\phi(T)$ can be approximated closely by a series of straight line segments, the equation of any one of which is

$$\phi(T) = K_1 T - K_2$$

where K_1 and K_2 are constants representing slope and intercept of straight lines tangent to heat loss curve.

Hence, along any one segment, equation A.2 may be expressed as

$$\delta \ell C \frac{dT}{dt} = I - (K_1 T - K_2)$$

or as

$$\frac{dT}{dt} + aT = bI + c \quad (\text{A.3})$$

where

$$a = \frac{K_1}{\delta \ell C}, \quad b = \frac{1}{\delta \ell C}, \quad \text{and } c = \frac{K_2}{\delta \ell C}$$

The solution of equation A.3 is

$$T = be^{-at} \left[F(t) - F(t_0) \right] + \frac{c}{a} \left[1 - e^{-a(t-t_0)} \right] + T_0 e^{-a(t-t_0)} \quad (\text{A.4})$$

where

$$F(t) - F(t_0) = \int_{t_0}^t e^{at} I dt$$

^{2/} Boelter, L.M.K., Cherry, V.H., and Johnson, H.A. Heat Transfer Notes. University of California Syllabus Series (2nd ed.). Berkeley, 1941.

~~SECRET~~

At the beginning of any given straight-line segment on the heat-loss curve, $t = t_0$ and $T = T_0$. At the end of the segment, $t = t$ and $T = T$. For a neighboring segment the values of a and c will change, since they depend on K_1 and K_2 . For values of T between 300°K and 375°K , the function $\phi(T)$ can be approximated by a single straight-line segment, and solutions can be readily found from equation A.4. This approximation may be used for computing the distance from ground zero that green foliage would be killed. When T is large, several straight-line segments must be used, and computations by means of equation A.4 become quite laborious.

The assumption of infinite thermal conductivity restricts the above analysis to a range of fuel weights from about 0.003 g/sq cm of frontal surface area to 0.010 g/sq cm . Even in this restricted range, an appreciable temperature difference will exist between the two surfaces of a flat fuel sample. To determine this temperature at any given time, as well as the temperature at any point within the fuel layer, it is necessary to solve the uni-directional heat flow equation:

$$\frac{K}{\delta c} \frac{\partial^2 T}{\partial X^2} = \frac{\partial T}{\partial t} \quad (\text{A.5})$$

where K is the thermal conductivity. The boundary conditions are:

$$K \left(\frac{\partial T}{\partial X} \right) = I - \phi(T) \quad \text{at } X = 0 \quad (\text{A.6})$$

and

$$K \left(\frac{\partial T}{\partial X} \right) = \phi(T) \quad \text{at } X = \ell \quad (\text{A.7})$$

The initial conditions are:

$$T = T_0 \quad \text{when } t \leq 0$$

and

$$\frac{\partial T}{\partial X} = 0 \quad \text{when } t = 0$$

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[REDACTED]

Solutions of equation A.5 could be obtained by the use of difference equations. The problem is complicated somewhat by distillation of water and volatile products and the resultant change in σ , C , and K . These changes will not occur simultaneously throughout the fuel layer but will start first on the irradiated side and progress through the fuel layer.

An alternate method which may be described as the reciprocity method is much simpler to use. It should be emphasized, however, that the reciprocity concept is valid only for fuels which conform to the infinite thermal conductivity concept.

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